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### Citation Details

Variability in Winter Mass Balance of Northern Hemisphere Glaciers and Relations with Atmospheric Circulation. Gregory J. McCabe, Andrew G. Fountain and Mark Dyurgerov. Arctic, Antarctic, and Alpine Research , Vol. 32, No. 1 (Feb., 2000), pp. 64-72

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# Variability in Winter Mass Balance of Northern Hemisphere Glaciers and Relations with Atmospheric Circulation

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## Abstract

An analysis of variability in the winter mass balance (WMB) of 22 glaciers in the Northern Hemisphere indicates two primary modes of variability that explain 46% of the variability among all glaciers. The first mode of variability characterizes WMB variability in Northern and Central Europe and the second mode primarily represents WMB variability in northwestern North America, but also is related to variability in WMB of one glacier in Europe and one in Central Asia. These two modes of WMB variability are explained by variations in mesoscale atmospheric circulation which are driving forces of variations in surface temperature and precipitation. The first mode is highly correlated with the Arctic Oscillation Index, whereas the second mode is highly correlated with the Southern Oscillation Index. In addition, the second mode of WMB variability is highly correlated with variability in global winter temperatures. This result suggests some connection between global temperature trends and WMB for some glaciers.

## Introduction

Glaciers are useful indicators of climatic variation because they change shape and size in response to climatic forcings. These changes are clearly visible and quantifiable. Because of the close connection between variations in climate and glacier size and shape, glacier variability is viewed as an indicator of climatic change. In addition, the advance and retreat of glaciers is important because of the practical implications for water supplies (Fountain and Tangborn, 1985) and hazards posed by glaciers (O'Connor and Costa, 1993; Walder and Fountain, 1998).

Global atmospheric circulation can be described by negative and positive anomalies of atmospheric pressure which extend across several hundreds to thousands of kilometers (Madden, 1979; Cayan and Peterson, 1989). Temporal and spatial variations in these pressure anomalies correlate with variations in surface weather variables such as temperature and precipitation (Klein, 1963; Namias, 1975, 1981; Wallace and Gutzler, 1981; Walsh et al., 1982; Weare and Hoeschele, 1983; Blackmon et al., 1984; Cayan and Roads, 1984; Alt, 1987; Klein and Bloom, 1987; Cayan et al., 1991; Cayan and Peterson, 1989; Knox and Lawford, 1990; Rohli and Henderson, 1998).

Most glacier/climate studies focus on studies of the relations between local climate and glacier mass balance (e.g.,  $10^1$  to  $10^3$  km<sup>2</sup>, Hoinkes and Rudolph, 1962; Tangborn, 1980; Mayo and Trabant, 1984). These studies are useful to understand detailed physical interactions between climate and glaciers. In contrast, studies on regional scales ( $10^4$  to  $10^6$  km<sup>2</sup>) often ignore details of local glacier/climate responses, but these mesoscale analyses often identify the primary climatic driving forces of glacier variability (Hoinkes, 1968; McCabe and Fountain, 1995; Pohjola and Rogers, 1997; Hodge et al., 1998). Several studies have investigated the relations between mesoscale climate (i.e. atmospheric circulation) and glacier mass balance (e.g., Hoinkes, 1968; Fahl, 1973; Meier et al., 1980; Yarnal, 1984; Walters and Meier, 1989; Brazel et al., 1992; McCabe and Fountain, 1995;

Pohjola and Rogers, 1997; Hodge et al., 1998; Bitz and Battisti, 1999). These studies discuss significant relations between variations in glacier mass balance and variations in atmospheric circulation, and have identified temporal co-variability of mass balances for many glaciers.

Because many glaciers respond to mesoscale climatic forcings and because the mass balances of glaciers within a region often co-vary, the objectives of this study are (1) to identify the primary modes of glacier variability in the Northern Hemisphere, and (2) determine how these modes of variability are related to variability in mesoscale atmospheric circulation.

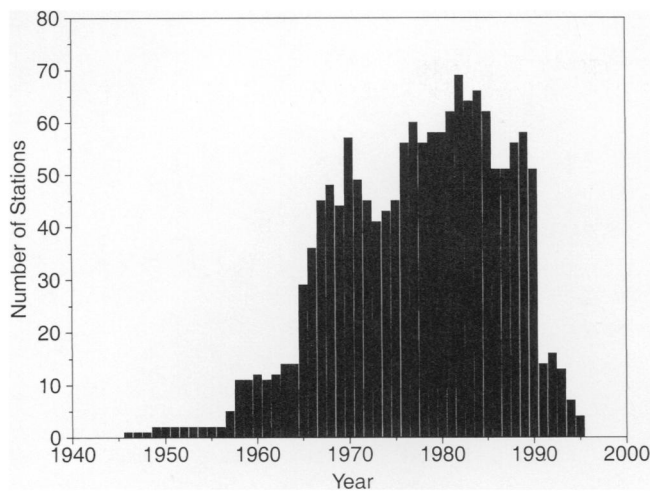
## Data and Methods of Analysis

### GLACIER DATA

The focus of this study is winter glacier mass balance (WMB). WMB was chosen for analysis because of the sensitivity of WMB to changes in mesoscale atmospheric circulation (Walters and Meier, 1989; McCabe and Fountain, 1995; Hodge et al., 1998; Bitz and Battisti, 1999). In addition, variability in atmospheric circulation is greatest during winter months and generally indicates relations with surface climate that are more identifiable and significant than during summer months.

Winter glacier mass balance is determined by two measurements: (1) the thickness of the snow accumulated during the winter season at different locations on the glacier, usually more than 20, and (2) the density of the snowpack. Together these two measurements are used to calculate the WMB and is expressed in water equivalent units. Although some snow loss due to wind or evaporation may occur during the winter season, WMB is a positive value as snow accumulation is greater than snow losses during the winter months.

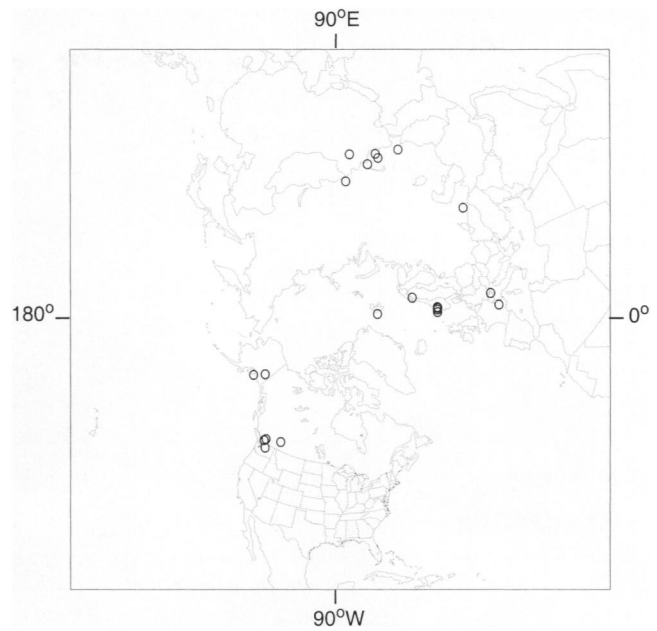
Winter glacier mass balance data are available for numerous glaciers in the Northern Hemisphere, however the period and length of record varies greatly (Fig. 1; Dyurgerov and Meier,



**FIGURE 1.** Number of glaciers in the Northern Hemisphere with winter mass balance data for each year from 1940 through 1995.

1997). The available records were searched to determine the period (at least 20 yr in length) with the greatest number of glaciers for which there are complete WMB records. Based on this search, 22 glaciers with complete data for the 1968 through 1989 period were chosen for analysis (Fig. 2, Table 1).

Principal components analysis is commonly used to identify groups of inter-related variables or groups of locations with a highly correlated variable (Johnston, 1980; Lins, 1985). In this study, principal components analysis (with varimax rotation) is used to identify the primary modes of variability in WMB for the 22 glaciers included in the study and to identify groups of glaciers with intercorrelated WMB. These modes are determined by identifying the components that explain the greatest amount of variability in the WMB data. The component scores charac-



**FIGURE 2.** Locations of glaciers analyzed in this study.

terize the temporal variability of each mode. In addition, the loadings (i.e. correlations) of WMB for individual glaciers on each component indicate groups of glaciers with covariation in WMB. Glaciers with loadings on a component that were significant at a 99% confidence level were considered to be a group of glaciers with intercorrelated WMB.

The glaciers for each group were mapped to identify regions of intercorrelated WMB. Additionally, time series of the component scores for selected principal components were analyzed and compared with winter atmospheric circulation to iden-

**TABLE 1**  
*Glaciers included in the study*

Glacier	Region	Latitude	Longitude	Max. elev. (m)	Min. elev. (m)	Area (km <sup>2</sup> )
Wolverine	Kenai Mtn.	60° 22' N	148° 54' W	1700	40	18
Gulkana	Alaska Range	63° 14' N	145° 28' W	2460	1200	19
South Cascade	Cascade Range	48° 22' N	121° 03' W	2140	1630	3
Place	Coastal Mtn. S.	50° 26' N	122° 36' W	2610	1860	4
Sentinel	Coastal Mtn. S.	49° 54' N	122° 59' W	2105	1660	2
Peyto	Rocky Mtn. N.	51° 40' N	116° 32' W	3185	2125	13
Alfotbreen	Alfotbreen	61° 45' N	5° 39' E	1380	890	5
Grasubreen	Jotunheimen	61° 39' N	8° 36' E	2300	1850	3
Hellstugubreen	Jotunheimen	61° 34' N	8° 26' E	2130	1470	3
Nigardsbreen	Jostodalsbreen	61° 43' N	7° 08' E	1950	355	48
Storbreen	Jotunheimen	61° 34' N	8° 08' E	1970	1380	5
Storglaciaren	Kebnekaise	67° 54' N	18° 34' E	1828	1125	3
Au. Broeggerbreen	Svalbard	78° 53' N	11° 50' E	600	60	6
Hintereisferner	Oetzaler Alps	46° 48' N	10° 46' E	3710	2391	10
Sarennes	French Alps	45° 07' N	6° 10' E	3190	3000	1
Djankuat	N. Caucasus	43° 12' N	42° 46' E	3990	2698	3
M.Aktru	Altaiy	50° 05' N	87° 45' E	3714	2229	3
Kara-Batkak	W. Tien Shan	42° 08' N	78° 16' E	4280	3287	5
Ur.Gl.No.1	E. Tien Shan	43° 05' N	86° 49' E	4486	3745	2
Tuyukso	N.W. Tien Shan	43° 00' N	77° 06' E	4219	3401	3
Abramov	Pamir	39° 40' N	71° 30' E	4960	3620	26
Shumskiy	Dzhungariya	45° 05' N	80° 14' E	4463	3126	3

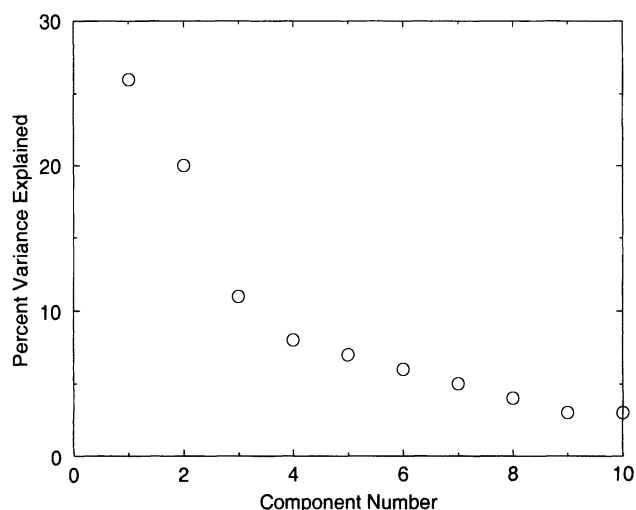


FIGURE 3. Percent of variance in winter mass balance for 22 glaciers in the Northern Hemisphere during the period 1968–1989 explained by each of 10 principal components.

tify relations between the primary modes of WMB variability and variability in atmospheric circulation.

#### ATMOSPHERIC CIRCULATION DATA

Atmospheric pressure heights for the 700-mb level were used to represent atmospheric circulation over the Northern Hemisphere. This pressure surface is approximately 3000 m above sea level and provides a good representation of mid-tropospheric atmospheric circulation, which controls seasonal weather variations (Cayan et al., 1991). Furthermore, studies have indicated that 700-mb heights are useful for identifying relations between atmospheric circulation and specific surface climate variables (Stidd, 1954; Klein, 1963; Cayan and Roads, 1984; Klein and Bloom, 1987; Cayan and Peterson, 1989; Knox and Lawford, 1990; Cayan et al., 1991; Dettinger and Cayan, 1992; McCabe, 1994; McCabe and Legates, 1995).

The 700-mb heights were obtained from gridded atmospheric pressure data produced by the Climate Analysis Center (CAC, Camp Springs, Maryland). 700-mb heights for the area from 20°N to 90°N were used. Daily values of 700-mb heights for October through April were averaged to produce winter mean 700-mb heights for the winters 1967–68 through 1988–89.

Correlations between principal component scores of the WMB data and the gridded winter 700-mb heights were computed and mapped. These correlations were used to identify relations between WMB and winter atmospheric circulation. Stidd (1954), Klein (1963), and Klein and Bloom (1987) found significant linear relations between 700-mb height anomalies and winter precipitation in the United States. The patterns indicated by such correlation fields are characteristic of the atmospheric circulation patterns associated with positive precipitation anomalies at a specific location. This approach can be used to identify relations between atmospheric circulation and other surface climate variables. McCabe (1994) and McCabe and Legates (1995) used this approach to examine the relations between winter mean 700-mb height anomalies and 1 April snowpack accumulations in the western United States. McCabe and Fountain (1995) successfully used this approach to examine relations between atmospheric circulation and the WMB of South Cascade and Wolverine glaciers in northwestern North America.

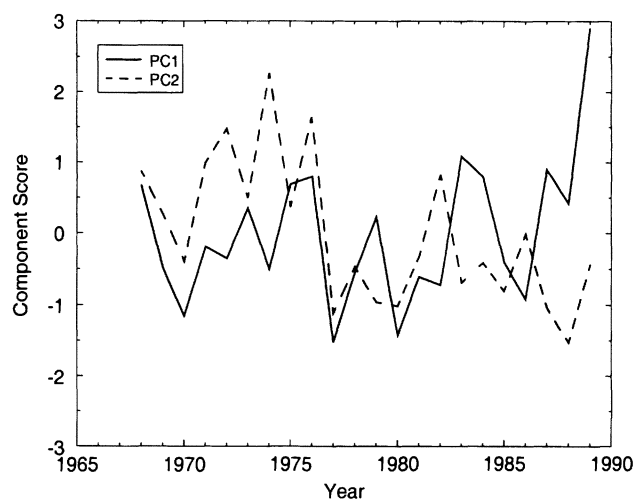


FIGURE 4. Time series of the scores of the first two principal components (PC1 and PC2) resulting from a principal components analysis of the winter mass balance of 22 glaciers in the Northern Hemisphere for the period 1968–1989.

#### TEMPERATURE AND PRECIPITATION

To aid the interpretation of the relations between WMB and atmospheric circulation, winter temperature and precipitation also were examined. Monthly temperature and precipitation data for the Northern Hemisphere were obtained for a 5 degree by 5 degree grid (National Oceanic and Atmospheric Administration's Climatological Baseline Gridded Data Over Land, National Climatic Data Center, Asheville, North Carolina). These data were used to compute winter mean (October through April) temperature and precipitation for the winters 1967–68 through 1988–89.

Similar to the analysis of 700-mb heights, correlations between the component scores of the WMB data and gridded winter temperature and precipitation data were computed. These correlations were mapped and compared with the correlation fields computed using the 700-mb data to identify relations between variability in WMB, atmospheric circulation, and winter temperature and precipitation.

### Results and Discussion

The principal components analysis of the WMB data for the 22 glaciers resulted in two components that explain 46% of the variance in WMB data (Fig. 3). The first component explains 26% of the variance in the WMB data, and the second component explains 20% of the variance. These two components were chosen for analysis as the remaining components only explain 50% or less of the variance explained by either of the first two components.

The time series of the scores for principal component 1 (PC1) represents the temporal variability of the WMB for the glaciers that loaded highest on this component (Fig. 4). PC1 exhibits values that varied for the most part from -1 to 1 up until the late 1980s when values increased sharply. The time series of scores for principal component 2 (PC2) indicate an interesting pattern in that the scores for the period before the mid-1970s were primarily positive, whereas the scores for the post-mid-1970s period were primarily negative. This change in the scores indicates a shift in mean WMB for the glaciers that loaded highest on PC2.

The loadings of WMB data on each of the first two com-

TABLE 2

Loadings of glacier winter mass balance on principal components 1 (PC1) and (PC2)

Glacier	PC1	PC2
Wolverine	-0.41904	<u>-0.57537</u>
Gulkana	-0.46260	-0.05624
South Cascade	0.00141	<u>0.90439</u>
Place	0.10029	<u>0.79827</u>
Sentinel	-0.01916	<u>0.71500</u>
Peyto	0.09525	<u>0.85209</u>
Alfotbreen	<u>0.78896</u>	0.34180
Grasubreen	<u>0.81535</u>	-0.30695
Hellstugubreen	<u>0.89699</u>	-0.09118
Nigardsbreen	<u>0.95000</u>	-0.01952
Storbreen	<u>0.97308</u>	0.05290
Storglaciaren	<u>0.77578</u>	0.24934
Au. Broeggerbreen	-0.07629	0.04768
Hintereisferner	<u>-0.55057</u>	0.24556
Sarennes	-0.25622	<u>-0.80120</u>
Djankuat	0.04197	-0.20074
M.Aktru	-0.26817	-0.30172
Kara-Batkak	-0.05468	0.14090
Ur.Gl.No.1	0.01972	0.39189
Tuyuksu	-0.18234	-0.17514
Abramov	0.03898	<u>-0.54791</u>
Shumskiy	-0.06942	0.19745

Loadings that are significant at a 99% confidence level are underlined and bold faced.

ponents were examined to determine which glaciers loaded highest on each of the two components (Table 2). Glaciers that load high on a component are temporally co-variant and this variability is characterized by the specific component. For each component, glaciers with loadings that were significant at a 99% confidence level were identified as glaciers with intercorrelated WMB.

Seven glaciers loaded highly on PC1 (Table 2). Six of these glaciers are located in northwestern Europe (Alfotbreen, Grasubreen, Hellstugubreen, Nigardsbreen, Storbreen, and Storglaciaren) and one is located in Central Europe (Hintereisferner) (Fig. 5). The six glaciers in northwestern Europe all loaded positively on PC1 whereas the glacier in Central Europe loaded negatively. This indicates that the WMB for the glacier in Central Europe is negatively correlated with the WMB of the glaciers in northwestern Europe.

Similar to PC1, seven glaciers also loaded highly on PC2 (Table 2). These glaciers are located primarily in northwestern North America (Wolverine, Gulkana, South Cascade, Place, Sentinel, and Peyto), however, one glacier is located in Central Europe (Sarennes) and another is located in Central Asia (Abramov) (Fig. 6). Four of the glaciers that loaded highly on PC2, have positive loadings. These four glaciers are located in western Canada and in the northwestern part of the conterminous United States. The three other glaciers that loaded highly on PC2 have negative loadings; one is in Alaska, one is Central Europe, and one is in Central Asia.

Correlations between the WMB for the eight other glaciers that did not load highly on these two components were small and did not indicate additional groups of WMB variability. WMB for these glaciers may be controlled primarily by local climatic, geographic, or topographic factors, and thus do not indicate significant correlations with other glaciers. Additionally, the bulk of the glaciers that did not load highly on the first two

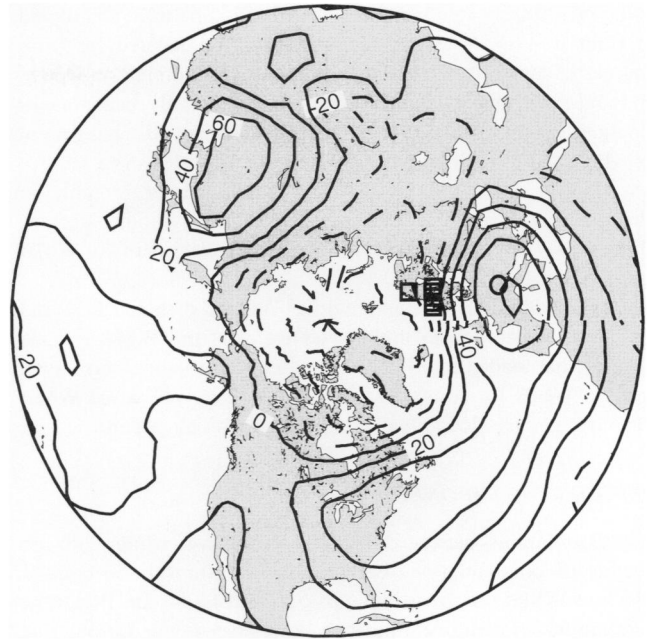


FIGURE 5. Correlations between the first principal component (PC1) and winter mass balance of glaciers that are significantly loaded on (correlated with) PC1 (Squares indicate glaciers with positive correlations and circles indicate glaciers with negative correlations), and winter (mean October through April) 700-mb heights (Solid lines indicate positive correlations and dashed lines indicate negative correlations; the first solid isoline is the zero correlation isoline; the correlations are multiplied by 100 and the contour interval is 10).

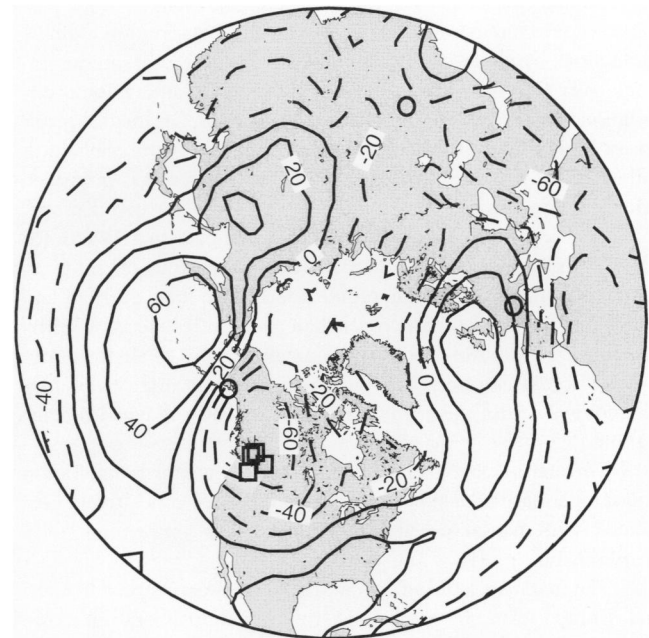


FIGURE 6. Correlations between the second principal component (PC2) and winter mass balance of glaciers that are significantly loaded on (correlated with) PC2 (Squares indicate glaciers with positive correlations and circles indicate glaciers with negative correlations), and winter (mean October through April) 700-mb heights (Solid lines indicate positive correlations and dashed lines indicate negative correlations; the first solid isoline is the zero correlation isoline; the correlations are multiplied by 100 and the contour interval is 10).

components are located in the Caucasus and one in Svalbard and in Central Asia. Many of these glaciers are located far from sources of atmospheric moisture and winter precipitation is low, and thus changes in atmospheric circulation only cause small changes in precipitation and subsequently small changes in WMB. In addition, many of the glaciers in Central Asia receive less than 40% of annual snowfall during winter months, so changes in summer glacier mass balance and summer surface climate may be more important for these glaciers than are WMB and winter climate.

Correlations between the winter 700-mb data and PC1 and PC2 were examined to understand why (1) the WMB for the glaciers that loaded highly on each component is intercorrelated, and (2) WMB for some glaciers loaded positively while WMB for other glaciers loaded negatively on each component.

#### PRINCIPAL COMPONENT 1

Correlations between scores for PC1 and winter 700-mb heights describe relations between winter atmospheric circulation and WMB for the glaciers that loaded highly on PC1. The correlation fields indicate positive correlations over Europe that extend westward into eastern North America, negative correlations over the Polar region that extend southward into Central Asia, and positive correlations over Eastern Asia (Fig. 5). The positive correlations are analogous to positive 700-mb height anomalies and the negative correlations are analogous to negative 700-mb height anomalies (Stidd, 1954; McCabe and Fountain, 1995).

For the six glaciers in northwestern Europe with positive loadings of WMB on PC1, the correlations between PC1 and winter 700-mb heights indicate that WMB is high when atmospheric pressures over the North Polar region are lower than average and pressures over Europe are higher than average. The negative pressure anomalies over the North Polar region indicate anomalous cyclonic circulation and the positive pressure anomalies over Central Europe indicate anomalous anticyclonic circulation. These coincident atmospheric pressure anomalies result in an increased flow of atmospheric moisture from the North Atlantic Ocean into Northern Europe. The net result is increased winter precipitation and winter temperatures in Northern Europe.

The negative of these correlations indicate that WMB for these six glaciers is lower than average when atmospheric pressures over the North Polar region are higher than average and pressures over Europe are lower than average. These atmospheric pressure conditions create an anomalous flow of air from east to west across Northern Europe which results in drier and colder air moving across the region, and subsequently reduced precipitation.

Correlations between PC1 and gridded winter precipitation and temperature data support these results. PC1 is positively correlated with winter precipitation and winter temperature over Northern Europe (Figs. 7a, 7b).

The negative loadings of WMB for Hintereisferner in Central Europe also are explained by the atmospheric pressure anomalies described by the correlations between PC1 and winter 700-mb heights. The correlations between PC1 and winter 700-mb heights indicate that Hintereisferner is located near the center of positive correlations (i.e. positive 700-mb height anomalies) (Fig. 5). These positive pressure anomalies indicate anomalous atmospheric subsidence over the region. The increased subsidence results in a warming and drying of the air and subsequently results in decreased winter precipitation and increased winter temperatures. In contrast, when atmospheric pressures

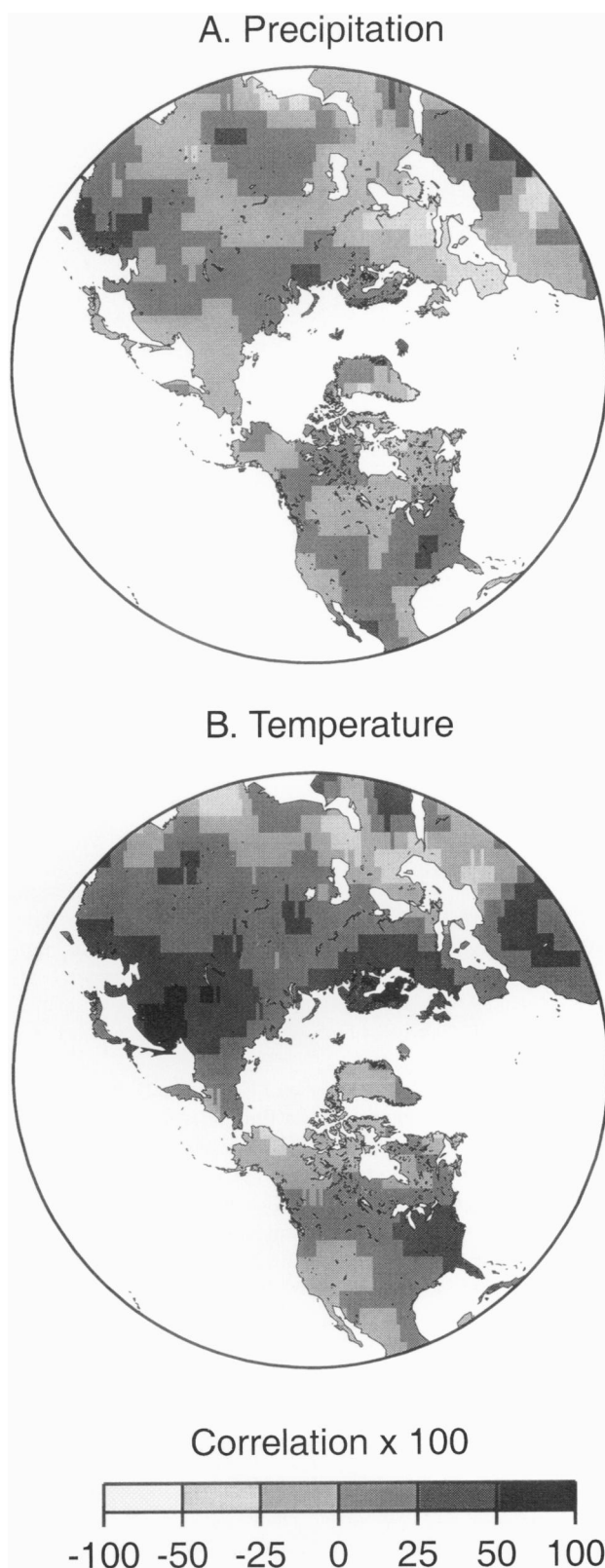


FIGURE 7. Correlations (multiplied by 100) between the first principal component (PC1) and (A) winter (total October through April) precipitation, and (B) winter (mean October through April) temperature.

over Europe are lower than average (i.e. negative 700-mb height anomalies), WMB at Hintereisferner is higher than average. Negative pressure anomalies indicate increased storm frequency and/or intensity which bring increased precipitation to the region. The correlations between PC1 and winter precipitation and temperature for the region around Hintereisferner indicate negative correlations with precipitation and positive correlations with temperature. These results are consistent with the expected surface climate anomalies associated with the atmospheric circulation indicated by the correlations between PC1 and winter 700-mb heights.

The sharp increase in the component scores for PC1 suggest a recent increase in WMB for the glaciers in northwestern Europe and a recent decrease for Hintereisferner. Based on the correlations between PC1 and winter 700-mb heights, these results indicate that the recent changes in WMB related with PC1 are due to recent changes in atmospheric circulation over Europe. For example, correlations between the scores of PC1 and various indices of atmospheric circulation indicate that PC1 is significantly correlated with the Arctic Oscillation Index (AO,  $r = 0.74$ ). The AO is the leading empirical orthogonal function of the wintertime sea-level pressure field poleward of 20°N (Thompson and Wallace, 1998). It is an index of the strength of the polar vortex and is closely related with surface climate variations over Europe. During recent years the AO has increased and has been connected with increasing temperatures in Europe.

## PRINCIPAL COMPONENT 2

The correlations between PC2 and winter 700-mb heights show positive correlations over the North Pacific Ocean and over the United Kingdom, and negative correlations over northwestern North America (Fig. 6). These correlations indicate that positive values of PC2 are related with positive 700-mb height anomalies over the North Pacific Ocean and the United Kingdom, and negative 700-mb height anomalies over northwestern North America.

In northwestern North America four glaciers are positively correlated with PC2 (South Cascade, Place, Sentinel, and Peyto), and one glacier (Wolverine) is negatively correlated with PC2 (Fig. 6). For positive values of PC2, positive 700-mb height anomalies occur over the North Pacific Ocean centered over the Aleutian Islands and negative 700-mb height anomalies occur over northwestern North America. This pressure pattern indicates a weakened Aleutian low and a weakening of the ridge of high pressure that generally exists over northwestern North America. The weakening of these pressure systems results in increased zonal atmospheric flow which decreases storm frequency in Alaska and increases storm frequency in northwestern North America. The result is decreased winter precipitation in Alaska and increased winter precipitation (and decreased temperature) in northwestern North America (McCabe and Fountain, 1995; Bitz and Battisti, 1999).

For negative values of PC2 positive 700-mb height anomalies occur over northwestern North America and negative height anomalies occur over the North Pacific Ocean. For negative values of PC2, WMB of glaciers in northwestern America is lower than average and WMB for Wolverine Glacier is higher than average. These atmospheric pressure anomalies result in a decrease in the frequency and/or the intensity of storms and the subsequent movement of moisture from the North Pacific Ocean into northwestern North America. In addition, the increase in winter mean 700-mb heights over northwestern North America results in an increase in atmospheric subsidence over the region,

which results in a warming and drying of the air that further reduces precipitation, and increases the ratio of rain to snow during the cold season. These same atmospheric circulation anomalies produce an enhanced southerly flow of air from the Gulf of Alaska into Alaska. This southerly flow promotes the intrusion of warm, moist air into Alaska and subsequently increases winter precipitation and the WMB of Wolverine Glacier (McCabe and Fountain 1995; Bitz and Battisti, 1999).

These relations between WMB in northwestern North America and winter atmospheric circulation are supported by correlations between PC2 and winter precipitation and temperature (Figs. 8a, 8b). PC2 is positively correlated with winter precipitation in northwestern North America and negatively correlated with precipitation in Alaska. In addition, PC2 is negatively correlated with winter temperatures in northwestern North America. Thus, positive values of PC2 are related with lower-than-average winter temperatures, and higher-than-average winter precipitation and WMB in northwestern North America, and lower-than-average winter precipitation and WMB in Alaska.

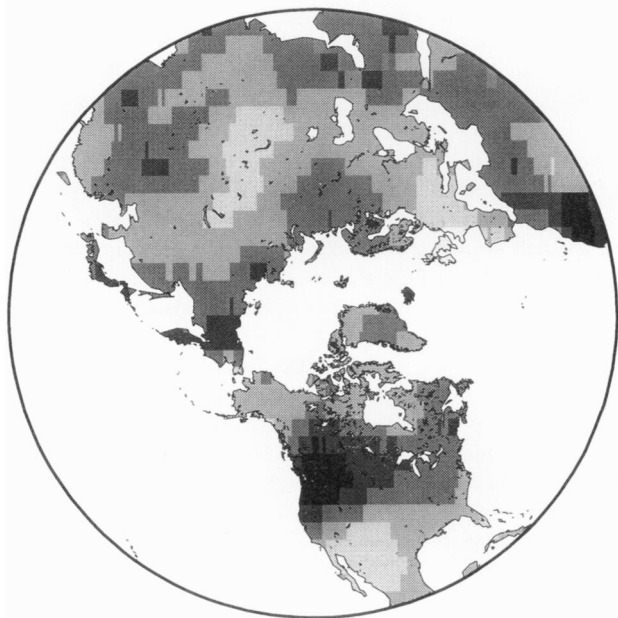
WMB of Sarennes Glacier in France is negatively correlated with PC2 (Fig. 6). For positive values of PC2 winter 700-mb height anomalies over most of Europe are positive and 700-mb height anomalies over Northern Africa are negative. This combination of anomalies produces an anomalous east-to-west flow of air from Central Europe. This air is generally drier than air that flows into Europe from the North Atlantic Ocean, therefore for these conditions winter precipitation is lower than average (Fig. 8a). For low values of PC2, WMB for Sarennes is higher than average and 700-mb height anomalies over Europe are negative and 700-mb height anomalies over Northern Africa are positive. This combination of pressures anomalies results in an anomalous flow of moist air from the North Atlantic Ocean into Central Europe which increases winter precipitation and WMB (Figs. 6, 8a).

The significant loadings of Abramov Glacier in Central Asia on PC2 are difficult to explain. WMB for Abramov Glacier is negatively loaded on PC2, however, correlations between PC2 and winter 700-mb heights indicate that lower than average WMB at Abramov Glacier is related to negative 700-mb height anomalies that stretch from the North Atlantic Ocean across Asia into the North Pacific Ocean (Fig. 6). Generally this 700-mb height anomaly pattern is indicative of increased storm activity through the region which produces increased winter precipitation. Correlations between PC2 and winter precipitation are positive for some parts of Southern Asia (Fig. 8a). These results are inconsistent with decreased WMB for Abramov Glacier. However, the driving force for decreased WMB at Abramov Glacier for positive values of PC2 may be increased winter temperatures. Correlations between PC2 and winter temperatures indicate positive correlations for a large part of Asia (Fig. 8b).

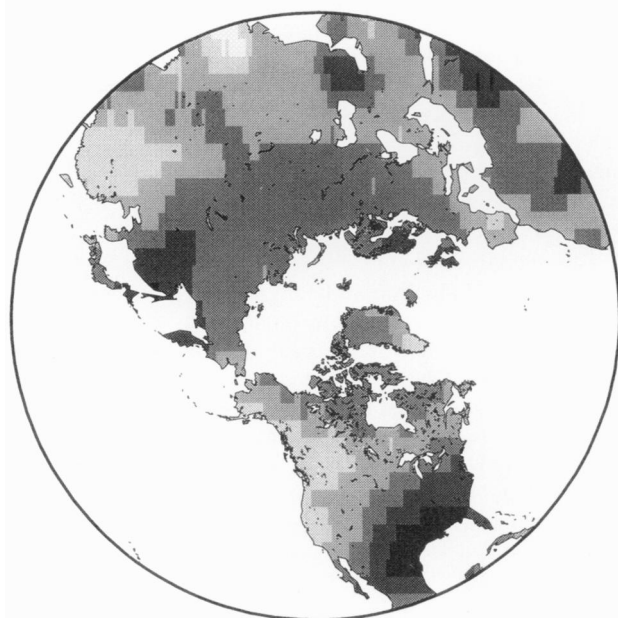
PC2 appears to primarily respond to changes in atmospheric circulation over the North Pacific Ocean and western North America. Correlations between PC2 and indices of atmospheric circulation indicate that PC2 is highly correlated ( $r = 0.60$ ) with the Southern Oscillation Index (SOI). SOI is an index of sea-level pressure differences across the tropical Pacific Ocean (Horel and Wallace, 1981; Redmond and Koch, 1991). Relations between SOI and surface climate are similar to those illustrated by the correlations between PC2 and winter precipitation and temperature (Figs. 8a, 8b). For example, SOI is positively correlated with precipitation in northwestern North America, and negatively correlated with precipitation in Alaska. Although variability in SOI primarily affects atmospheric circulation and surface climate in the Western Hemisphere, teleconnections between SOI



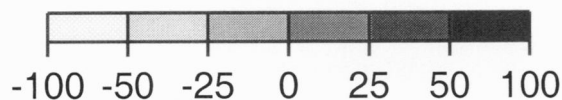
## A. Precipitation



## B. Temperature



Correlation x 100



**FIGURE 8.** Correlations (multiplied by 100) between the second principal component (PC2) and (A) winter (total October through April) precipitation, and (B) winter (mean October through April) temperature.

and surface climate in Europe also have been identified (Fraedrich and Muller, 1992; Wilby, 1993). Fraedrich and Muller (1992) found that warmer-than-average sea-surface temperatures in the tropical Pacific Ocean (i.e. negative SOI episodes) are associated with more frequent and/or intense storms in Central Europe, which increase winter precipitation and decrease winter temperatures. These results are consistent with the correlations between PC2 and winter precipitation and temperature in Europe (Figs. 8a, 8b).

The scores of PC2 indicate a shift during the mid-1970s from primarily positive values to primarily negative values (Fig. 4). Based on the shift in PC2, and the loadings of WMB on PC2, it is evident that since the mid-1970s WMB has decreased for South Cascade, Place, Sentinel, and Peyto glaciers in northwestern North America, increased at Wolverine Glacier, and decreased at Sarennes and Abramov glaciers. These trends in WMB appear to be related to the mid-1970s climate transition (Miller et al., 1993).

Miller et al. (1993) identified an abrupt shift in the basic state of the atmosphere-ocean climate system over the North Pacific Ocean during the 1976–77 winter season. The Aleutian Low deepened, causing storm tracks to shift southward and to increase storm intensity (Folland and Parker, 1990; Trenberth, 1990). In northwestern North America, atmospheric pressures increased resulting in increased winter temperatures and decreased winter precipitation (Cayan and Peterson, 1989). This shift in climate was illustrated by Ebbesmeyer et al. (1991) in a composite time series of 40 environmental variables, which suggests an abrupt change in climate during the winter 1976–77.

In addition, to changes in atmospheric pressures over the North Pacific Ocean and North America during the mid-1970s, atmospheric pressures over the central North Atlantic Ocean and most of Europe decreased, and atmospheric pressures over Northern Africa and Central Asia increased. These changes in atmospheric circulation promoted the development of an anomalous flow of moist air from the North Atlantic Ocean into Europe.

In a previous study, McCabe and Fountain (1995) determined that the mid-1970s climate shift was primarily responsible for the decrease (becoming more negative) in net mass balance of South Cascade Glacier, and the simultaneous increase (becoming more positive) in the net mass balance of Wolverine Glacier since the mid-1970s. Cao (1998) examined decadal-scale changes in the mass balance of three glaciers in the Tien Shan Mountains. Cao found an abrupt change in glacier mass balance in the Tien Shan Mountains and attributes this change to the mid-1970s climate transition that was initiated in the tropical Pacific Ocean. Cao's results are consistent with the results presented here.

### EFFECTS OF VARIABILITY IN GLOBAL TEMPERATURES

Because the mass balance of several glaciers throughout the Northern Hemisphere have decreased during recent years, there is speculation that these decreases are a result of increases in global temperatures (Mayo and Trabant, 1984; Intergovernmental Panel on Climate Change, 1992). Correlations between global mean winter (October through April) temperatures for the years 1968 through 1989 and scores for PC1 and PC2 are 0.17 and –0.70, respectively. These results indicate a significant correlation between global mean winter temperature and PC2 (Fig. 9). At least for the 1968 through 1989 period there has been some connection between increases in global temperatures, changes in atmospheric circulation, and changes in WMB for some glaciers in the Northern Hemisphere. It is unclear, however, from this



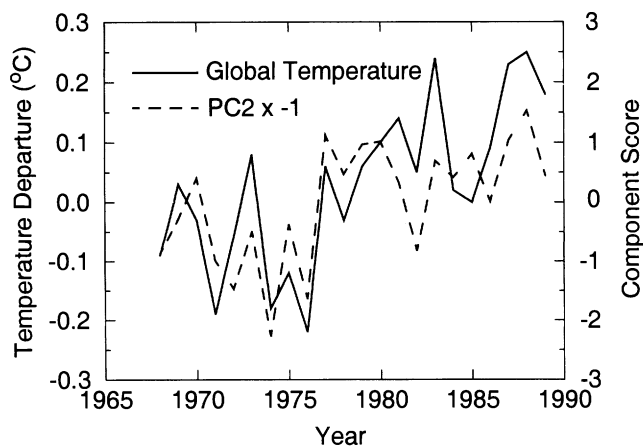


FIGURE 9. Comparison of global mean winter (October through April) temperature and scores for principal component 2 (PC2) for the period 1968 through 1989 (PC2 is multiplied by  $-1$  for direct comparison with the temperature data).

analysis whether the increases in temperatures produced the changes in atmospheric circulation or vice versa. It is interesting to note that the glaciers that loaded highest on PC1 do not seem to have been affected significantly during the 1968–1989 period by increases in global mean winter temperature.

## Conclusions

WMB data for 22 glaciers in the Northern Hemisphere were subjected to a principal components analysis to identify the primary modes of WMB variability in the Northern Hemisphere. Two components resulted that explain 46% of the variability in WMB among the 22 glaciers. The variability in these principal components is explained by variability in atmospheric circulation and related variability in winter precipitation and temperature.

The results of this study illustrate that (1) variability in WMB for many glaciers in the Northern Hemisphere is related to variability in mesoscale atmospheric circulation, (2) some Northern Hemisphere glaciers indicate a significant shift in WMB since the mid-1970s which is related to changes in mesoscale atmospheric circulation and global temperature, and (3) measured glacier data are limited both temporally and spatially, these records need to be expanded to better understand the relations between glacier mass balance and climatic driving forces.

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Ms submitted April 1999